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PHYSIOLOGIC STRAIN ASSOCIATED WITH WEARING TOXIC-ENVIRONMENT PROTECTIVE SYSTEMS DURING EXERCISE IN THE HEAT

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The new generation Self-Contained Toxic-Environment Protective Outfit was tested in its two configurations, one with a backpack rebreather-respirator and a liquid-cooling vest (STEPO-R), and one tethered to an air supply providing cooling and breathing air (STEPO-T). Also tested was the currently fielded Toxic Agent Protective (TAP) Suit. Six soldiers volunteered to be evaluated during exercise and rest in 27°C, 38°C, and 49°C environments while wearing the protective systems. The STEPO-T allowed the longest endurance time, while STEPO-R reduced endurance and increased physiological strain relative to the other systems.

INTRODUCTION

For individuals who work with the storage, maintenance and disposal of toxic substances, protective garments are essential. In an effort to provide US Army personnel with the best possible protection in a practical garment, the U.S. Army Natick Research, Development and Engineering Center has continued development of the Self-Contained Toxic-Environment Protective Outfit (STEPO). This garment system has been designed to replace the currently fielded Toxic Agent Protective (TAP) Suit which has been in use for more than 30 years. The improvements made to the STEPO systems include a backpack rebreather-respirator and a microclimate cooling system, or a tether option supplying breathing and cooling air inside the suit, intended to enhance breathing air quality and reduce thermal strain.

Toxic-environment protective clothing is characterized by low moisture permeability. The physiological strain associated with exercise and/or heat exposure is exacerbated when individuals must perform physical work while wearing protective clothing that acts as a barrier to sweat evaporation. Pimental et al. (1987) and Muza et al. (1988) have documented the thermoregulatory consequences for individuals wearing protective clothing with and without

microclimate cooling. The effectiveness of microclimate cooling systems in reducing heat strain for persons working in protective clothing has been reviewed by Speckman et al. (1988).

The present study reports results concerning the physiological evaluations of the second generation STEPO systems. The results of testing on the prototype STEPO were presented last year at this meeting (Pandolf et al., 1989). Compared to the prototype, the new STEPO systems employ improved weight distribution for the backpack rebeather-respirator, prolonged microclimate cooling capacity, and a teflon-fiberglass suit fabric to replace the butyl rubber-coated nylon.

METHODS

Subjects

Six male soldiers volunteered to be test subjects following medical clearance and after signing a statement of informed consent. Investigators adhered to AR 70-25 and USAMRDCR 70-25 concerning the use of volunteers in research. The physical characteristics ($\bar{X}\pm SD$) of the volunteers were as follows: age, 25±9 yr; ht, 176±6 cm; wt, 74± 5 kg; body fat, 16±6 %; and, maximal aerobic power ($\dot{V}o_2max$), 53±7 ml O_2/kg/min.

Test garments

All three protective ensembles are impermeable and totally encapsulating, and include protective masks, rubber gloves and boots. Under each test garment, subjects wore a layer (long pants, long sleeves, socks) of light cotton clothing and standard tropic-style combat boots. The STEPO garments are fabricated from a teflon/fiberglass laminate, while the TAP suit is of butyl rubber-coated nylon. STEPO-R incorporates a backpack (16 kg) rebreather-respirator carried in an enclosed pod outside the suit. The total STEPO-R ensemble including the microclimate liquid-cooled vest weighs ~30 kg. The microclimate cooling system supplies a total of ~200W of cooling to the torso via the liquid-cooled vest, and to the breathing air in the mask via a heat-exchanger. The STEPO-T system is tethered to compressed breathable air (ambient temperature) which is blown into the suit for cooling, and into the mask for breathing. Also included in the STEPO-T system is an emergency air supply carried in a compressed air cylinder. Total weight of the STEPO-T ensemble is ~12 kg. The TAP suit includes the M17 protective mask but does not include a cooling system, and weighs ~8 kg.

Experimental design

For each test subject, $\dot{V}o_2max$ was determined using a continuous treadmill exercise protocol (Sawka, 1985). Subjects were fitted with the protective garments, and each practiced walking on the treadmill on at least four familiarization sessions preceeding testing.

During the 10 days preceding testing, the subjects participated in an exercise-heat acclimation program.

Acclimation (Accl) consisted of daily treadmill walking (1.56 m/sec, 4% grade) for 120 min in the heat(42°C, ~35%rh). During Accl, subjects wore shorts, t-shirt, socks, and comfortable athletic shoes. They were allowed to drink water ad libitum, but were encouraged to drink enough to maintain euhydration.

Following Accl, the three protective ensembles were tested in warm (27°C, ~50%rh) and hot (38°C,~30%rh) environments. The warm environment was selected as representative of a summer day in the northern or central United States, while the hot condition was selected to represent a summer day in the southern United States. Within each environment, tests were administered in a counterbalanced order, and each subject served as his own control. The exercise-heat tests (EXT) consisted of alternate bouts of level treadmill walking for 45 min (1.12 m/sec) and seated rest for 15 min. The exercise intensity was determined (during a field study) based on metabolic measurements of a simulated toxic clean-up scenario by personnel in TAP suits. Subjects attempted to complete four exercise/rest cycles, for a total of 4 h. During all exercise bouts and all but the first rest period, subjects remained totally encapsulated. Only during the first rest period did subjects remove the hood/mask and drink water ad lib.

Experiments were also conducted in a very hot (49°C, ~15% rh) environment, in order to examine the capability of personnel to work in a representative condition. For these experiments, only the STEPO-T, and a variation of the STEPO-T worn with the microclimate cooling vest (STEPO-TV) were tested.

Experimental procedures

Heart rate (HR), was obtained from an electrocardiogram telemetered to and displayed on an oscilloscope cardiotachometer unit. Rectal temperature (T_{re}) was measured via a flexible thermistor inserted ~10 cm beyond the anal sphincter. Skin temperature was measured at three points (forearm, chest, calf) by thermocouples and mean weighted skin temperature ($\bar{T}_{sk}$) was calculated (Burton, 1935). Additionally, a thermocouple was used to measure the temperature between the top of the subject's head and the hood of the garment (T_{hd}). All temperatures were continuously monitored. Sweating rates were determined from nude body weight changes pre- to post-exercise, corrected for water ingestion. Corrections for unevaporated sweat left in the garments were used to calculate percent evaporative sweat.

Metabolic rates were determined via open circuit spirometry, during the familiarization sessions. The suits were opened and masks were removed to allow for collection of expired gases. For a subjective measure of how the test subjects felt during the EXT, at 20 and 40 min of each hour, subjects were asked to rate their perception of effort (RPE) using a numbered scale from 6-20 (Borg, 1970), and their thermal sensation (TS) using a numbered scale from 0-8 (Gagge

et al., 1967; Young et al., 1987).

During Accl and EXT, subjects were removed from testing if HR exceedeed 180 bpm for five consecutive min, or if T_{re} reached 39.5°C. The test subjects withdrew themselves if they felt faint, sick or otherwise unable to continue. If there was a malfunction in any protective system that could not be corrected within 5 min, that test was terminated, and repeated on a later date.

Statistical treatment

Data were analyzed using a repeated measures analysis of variance. Tukey's post hoc test was employed to locate significant ($P<0.05$) differences. Because of small and unequal sample sizes during the 49°C experiments (n=3 for STEPO-T, n=6 for STEPO-TV), statistics were not performed on data for the very hot tests. Data are reported as means ± standard deviation ($\bar{X}\pm SD$).

RESULTS

The subjects' metabolic rates during exercise were: 312±45, 356±36, 424±36 and 493±93 watts when they were wearing shorts, TAP, STEPO-T and STEPO-R, respectively. These metabolic rates of 23, 24, 31 and 36% of $\dot{V}o_2max$ are representative of light to moderate exercise. Both STEPO systems elicited higher ($p<0.05$) metabolic rates than either shorts or the TAP suit.

Figure 1 presents endurance time for the subjects in each experimental condition. In the warm environment, endurance time was longer ($p<0.05$) for subjects in STEPO-T (219±51 min) than STEPO-R (111±76 min), but for the TAP suit endurance time (194±56 min) was not different. During the STEPO-T experiments, five subjects were able to complete the entire 240 min session. One subject was removed from testing for the day because his core temperature reached the safety criteria. During the STEPO-R experiments, four subjects removed themselves from testing due to muscular discomfort (sore, tired backs and/or legs), and one because of mask/visor fogging. Only one subject completed 240 min. During the TAP experiments, three subjects completed the session, and three discontinued due to muscular discomfort (one was nearing HR criteria).

In the hot environment, endurance times were not significantly different among the systems (STEPO-T, 82±52 min; STEPO-R, 57±27 min; TAP, 56±20 min). During the STEPO-T experiments, five subjects discontinued because of physiological discomfort (hot, light-headed, breathing discomfort), and one was removed upon achieving the safety criteria for heart rate. During the STEPO-R experiments, three subjects discontinued because of muscular discomfort, and three discontinued due to physiological discomfort. For the TAP experiments, five subjects discontinued due to physiological discomfort (one was nearing HR criteria, and one was nearing T_{re} criteria), while one subject did reach the criteria HR.

Figure 1. Endurance time for three protective ensembles (and one variation, STEPO-TV) in warm, hot and very hot environments. At 27°C, time for STEPO-T > STEPO-R ($p<0.05$).

Table 1 presents the subjects' final exercise thermoregulatory, heart rate and perceptual responses. In addition, the change in T_{re} (ΔT_{re}) from rest to the latest time when all subjects were still testing, is presented (0-45 min in the warm, and 0-25 min in the hot environment). In the warm environment, differences ($p<0.05$) were observed for final $\bar{T}_{sk}$ (STEPO-R < TAP) and for final HR (STEPO-R < TAP and STEPO-T). In the hot environment, the ΔT_{re} was greater ($p<0.05$) during STEPO-R than STEPO-T, and final HR was lower ($p<0.05$) for STEPO-R than TAP. Final RPE was greater ($p<0.05$) for the STEPO-R than for either TAP or STEPO-T. Body temperatures and HR were also analyzed over time in each environment, and all but T_{hd} increased as time progressed. However, only T_{hd} values were significantly different among the three protective garments in the hot environment. Values for T_{hd} in the TAP suit were consistently higher than for STEPO-R, which were consistently higher than for STEPO-T.

In the very hot environment only STEPO-T and STEPO-TV were tested. Because of the extreme environment, only three subjects were tested wearing STEPO-T on one day, and based on their enhanced discomfort and very short endurance times, the other three subjects did not test. Table 2 presents the final test data for the very hot environment.

Table 1. Final exercise temperature, heart rate and perceptual responses for men exercising in warm and hot environments while wearing toxic-protective clothing.

	TAP		STEPO-R		STEPO-T	
	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD
27°C Environment						
T_{re} (°C)	38.6	0.5	37.9	0.4	38.3	0.6
ΔT_{re} (°C/45 min)	0.6	0.2	0.7	0.2	0.6	0.1
$\bar{T}_{sk}$ (°C)	36.3	0.7	34.6*	1.7	35.6	0.6
T_{hd} (°C)	33.3	2.1	33.6	1.9	31.6	2.7
HR (bpm)	155	21	130*†	22	147	23
TS	6.8	0.7	4.8	0.8	5.6	0.9
RPE	15.3	3.1	16.8	1.5	14.8	2.8
38°C Environment						
T_{re} (°C)	38.8	0.7	38.5	0.7	38.3	0.4
ΔT_{re} (°C/25 min)	0.6	0.1	0.7†	0.1	0.5	0.1
$\bar{T}_{sk}$ (°C)	38.4	0.8	37.4	1.6	37.9	0.7
T_{hd} (°C)	39.3	1.0	37.3	0.7	35.6*	1.7
HR (bpm)	172	18	155*	7	162	15
TS	6.7	0.6	6.8	0.4	6.2	0.9
RPE	13.5	3.1	17.2*†	0.4	14.0	2.6

*P<0.05 compared to TAP; †P<0.05 compared to STEPO-T.

Table 2. Final exercise temperature, heart rate and perceptual responses for men exercising in a very hot environment while wearing toxic-protective clothing.

	STEPO-T (n=3)		STEPO-TV (n=6)	
	$\bar{X}$	SD	$\bar{X}$	SD
49°C Environment				
T_{re} (°C)	37.9	0.6	38.4	0.6
ΔT_{re} (°C/25 min)	0.5	0.1	0.6	0.2
$\bar{T}_{sk}$	38.9	1.9	36.6	1.2
T_{hd}	39.8	3.4	39.3	3.0
HR (bpm)	171	11	168	15
TS	6.3	0.6	6.8	0.5
RPE	13.3	3.2	14.7	1.8

Table 3. Sweating rate and percent of total sweat which was evaporated (% evaporation).

	TAP		STEPO-R		STEPO-T		STEPO-TV	
	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD
27°C Environment								
Sweating Rate ($g/m^2/h$)	494	88	570	222	395	143	-	-
% Evaporated	30†	9	24†	9	57	13	-	-
38°C Environment								
Sweating Rate ($g/m^2/h$)	1029	253	914	240	885	301	-	-
% Evaporated	33	5	38	11	49	4	-	-
49°C Environment								
Sweating Rate ($g/m^2/h$)	-	-	-	-	813	192	803	168
% Evaporated	-	-	-	-	29	0	43	11

†$P<0.05$ compared to STEPO-T.

Table 3 presents total sweating rates and percent sweat evaporated for each environment. Statistics were performed on both variables for the warm experiments, only on the total sweating rates for the hot experiments, and no statistics were performed for the very hot environments. In the warm environment, the percent sweat evaporated was greater ($p<0.05$) for the STEPO-T than for either the STEPO-R or TAP. During all the experiments, the subjects' rate of dehydration ranged from 1.2 to 2.5% of body weight per hour.

DISCUSSION

Toxic-protective clothing severely limits heat exchange between the individual and the environment. Additionally, the bulk of the clothing and that of associated equipment renders movement to be less efficient as well as adding weight that must be carried. These factors add to the energy cost of a given task, and result in an additional heat load which needs to be dissipated. Clearly, the heavier the protective system in this study the greater the energy cost for a given task.

One half of all the STEPO-R experiments were terminated because of severe muscular discomfort. In the previous STEPO study (Pandolf et al., 1988), two of seven subjects suffered back spasms, one in each of the STEPO systems. Further refinement/development of the load carriage for the STEPO-R system is needed.

The STEPO systems were designed to reduce thermal stress and extend work tolerance relative to the TAP suit. In the warm environment, STEPO-T allowed longer endurance times while

STEPO-R was clearly inferior. In the hot condition most indices of thermal strain were comparable among suits, although with STEPO-T non-significant benefits were observed. Improvement in the microclimate cooling capacity would enhance the STEPO-R, and inclusion of an air-cooling vest next to the skin for STEPO-T would improve this system as well. Finally, the capability of carrying and drinking ~2 liters of water would minimize dehydration and undoubtedly enhance performance.

DISCLAIMER AND DISTRIBUTION STATEMENT

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